10/576120
IAP15 Rec'd PCT/PTO 18 APR 2006

Description

PHOTOMASK AND PATTERN FORMATION METHOD AND MASK DATA GENERATION METHOD USING THE SAME

Technical Field

The present invention relates to a photomask for use in forming a fine pattern in fabrication of a semiconductor integrated circuit device or the like and a design method for the same.

Background Art

Recently, there are increasing demands for further refinement of circuit patterns for increasing the degree of integration of a large scale integrated circuit device (hereinafter referred to as the LSI) realized by using semiconductor. As a result, it has become very significant to thin an interconnect pattern included in a circuit.

Now, the thinning of an interconnect pattern by a conventional optical exposure system will be described on the assumption that positive resist process is employed. In this case, a line pattern means a portion of a resist film not exposed to exposing light, namely, a resist portion (a resist pattern) remaining after development. Also, a space pattern means a portion of the resist film exposed to the exposing light, namely, an opening portion (a resist removal pattern) formed by removing the resist through development. In the case where negative resist process is employed instead of the positive resist process, the definitions of the line pattern and the space pattern are replaced with each other.

When a pattern is formed by using the optical exposure system, a photomask in which a completely shielding pattern of Cr (chromium) or the like is drawn in accordance with a desired pattern on a transparent substrate (a permeable substrate) of quartz or the

like is conventionally used. In such a photomask, a region where the Cr pattern exists is a shielding portion that does not transmit exposing light of a given wavelength at all (having transmittance of substantially 0%) and a region where no Cr pattern exists (an opening) is a transparent portion that has transmittance equivalent to that of the transparent substrate against the exposing light (having transmittance of substantially 100%). In the case where a wafer on which a resist is applied is subjected to exposure by using this photomask, the shielding portion corresponds to an unexposed portion of the resist and the opening (the transparent portion) corresponds to an exposed portion of the resist. Accordingly, such a photomask, namely, a photomask composed of a shielding portion and a transparent portion against exposing light of a given wavelength, is designated as a binary mask.

It is, however, difficult to form a fine pattern smaller than the exposure wavelength (the wavelength of the exposing light) by using the binary mask due to the diffraction phenomenon of light. Therefore, a mask pattern having a function to invert the phase of light, namely, a photomask provided with a phase shifter, is recently used. Furthermore, as a photomask for largely increasing the contrast and DOF (depth of focus) in fine pattern formation, a mask having a mask enhancer structure (an image enhancement mask) devised by the present inventor may be used in pattern formation. The mask enhancer structure basically includes a phase shifter and a shielding pattern such as a Cr pattern (see, for example, International Application PCT/JP00/07772 laid open in accordance with Patent Cooperation Treaty (International Publication No. W0 01/35166 A1), hereinafter referred to as Literature 1).

FIG. **19A** shows an exemplified plane structure of an image enhancement mask, and FIG. **19B** shows light amplitude intensity obtained through exposure of the mask of FIG. **19A** on a material to be exposed in a position corresponding to a line **AA'**.

As shown in FIGS. **19A** and **19B**, a transparent phase shifter is provided within a

pattern of a shielding film such as a Cr film (a shielding portion) in the image enhancement mask, so that the contrast in a light intensity distribution formed in the exposure can be enhanced.

The image enhancement mask of FIG. **19A** is obtained by combining a mask shown in FIG. **19C** in which a shielding portion (a shielding pattern) is surrounded with a transparent portion and a mask shown in FIG. **19D** in which a phase shifter is surrounded with a shielding portion. FIG. **19E** shows the light amplitude intensity obtained through the exposure of the masks of FIGS. **19C** and **19D** on materials to be exposed in positions corresponding to lines **AA'**.

As shown in FIGS. **19C** and **19E**, in the light intensity distribution formed in the case where a mask including a line-shaped shielding portion (specifically a Cr pattern) alone is used, as the line width of the Cr pattern is smaller, the light intensity obtained at the center of the Cr pattern (namely, the mask pattern center) is increased owing to light rounding the periphery of the Cr pattern. In other words, it cannot sufficiently shield the light although it is a shielding pattern. Accordingly, a sufficient shielding property cannot be realized, resulting in lowering the contrast in the light intensity distribution.

On the other hand, as shown in FIGS. **19D** and **19E**, in the case where a phase shifter for transmitting light in an opposite phase with respect to the transparent portion is used, if light passing through the phase shifter and light passing through the transparent portion can be made interfere with each other, these light cancel each other. Accordingly, with respect to a pattern having a line width too small to sufficiently shield light by using a Cr film, when a transparent phase shifter is formed within the Cr pattern, light passing through the phase shifter can be made to interfere with light passing through the transparent portion disposed around the Cr pattern and rounding to the back side of the Cr pattern, resulting in realizing a mask pattern having a very high shielding property. Such

a structure in which a phase shifter for canceling light passing through a transparent portion is provided within a mask pattern with a shielding property is designated as a mask enhancer structure.

Although the mask enhancer structure is described to be composed of a shielding film such as a Cr film and a phase shifter in the above description, the equivalent effect can be attained when the shielding film is replaced with a semi-shielding film. A semi-shielding film partially transmits light, and light passing through the semi-shielding film and light passing through the transparent portion are in an identical phase.

Also, in pattern formation using a mask having the mask enhancer structure, the contrast in the light intensity distribution is increased/reduced as well as a process margin is increased/reduced in accordance with the combination of the width of the Cr film and the width of the phase shifter. The aforementioned Literature 1 discloses, as a method for increasing a process margin in formation of an isolated pattern, that a thin phase shifter is provided within a thick Cr pattern and a thick phase shifter is provided within a thin Cr pattern.

In the case where the mask enhancer structure is employed in a photomask including an isolated pattern alone, a large process margin can be attained by providing a thin phase shifter within a thick Cr pattern and a thick phase shifter within a thin Cr pattern as described above. However, in the case where the mask enhancer structure is employed in a photomask not only including an isolated pattern but also having complicated patterns mixedly having arbitrary pattern layouts, the process margin cannot be sufficiently increased simply by changing the width of the phase shifter in accordance with the width of the Cr pattern.

Disclosure of the Invention

In consideration of the aforementioned disadvantage, an object of the invention is attaining an effect to sufficiently increase a process margin even when the mask enhancer structure is employed in a photomask having complicated patterns mixedly having arbitrary pattern layouts.

In the case where a pattern to be applied for the mask enhancer structure is close to another pattern, conditions for increasing a process margin are complicated for the following reason: Also in a general binary mask, when a target pattern is close to another pattern, the dimension and the shape of the mask should be changed in consideration of the close pattern. In general, such an operation is designated as OPC (optical proximity correction). Accordingly, it is difficult to increase a process margin in exposure using a photomask having complicated patterns mixedly having arbitrary pattern layouts simply by determining the architecture of the pattern having the mask enhancer structure on the basis of the line width of the pattern.

Therefore, the present inventor has variously examined a mask architecture capable of increasing a process margin even when a pattern to be applied for the mask enhancer structure is close to another pattern. As a result, it has been found that a process margin can be increased even in complicated patterns mixedly having arbitrary pattern layouts by employing a mask architecture in which the width of a phase shifter included in the mask enhancer structure of the pattern is made smaller as a distance from another close pattern is smaller.

The present invention was devised on the basis of the aforementioned finding, and specifically, the first photomask of this invention includes a mask pattern formed on a transparent substrate; and a transparent portion of the transparent substrate where the mask pattern is not formed, and the mask pattern includes a first pattern and a second pattern each having a mask enhancer structure including a phase shifter for transmitting exposing

light in an opposite phase with respect to the transparent portion and a shielding portion surrounding the phase shifter, the first pattern is close to a third pattern included in the mask pattern at a distance not larger than a given distance with the transparent portion sandwiched therebetween, and a width of the phase shifter of the mask enhancer structure of the first pattern is smaller than a width of the phase shifter of the mask enhancer structure of the second pattern.

In the first photomask, the width of the phase shifter of the mask enhancer structure of the first pattern close to another pattern (the third pattern) at a distance not larger than the given distance is relatively small. Therefore, in accordance with the degree at which light (in an identical phase with respect to the transparent portion) rounding to the back side of the first pattern through the transparent portion disposed around the first pattern is reduced owing to the close pattern, light (in an opposite phase with respect to the transparent portion) passing through the inside (the phase shifter) of the first pattern can be reduced. Accordingly, the shielding property of the first pattern can be sufficiently improved, and hence, an exposure margin is increased and contrast in a light intensity distribution formed in the exposure is improved. In other words, also in a photomask including not only an isolated pattern but also complicated patterns close to one another, the effect to increase a process margin can be sufficiently attained by employing the mask enhancer structure. Also, since the width of the phase shifter of the mask enhancer structure can be optimized in accordance with the close relationship between patterns, a photomask capable of fine pattern formation with random pattern layout can be realized.

In the first photomask, each of the first and second patterns is, for example, a line pattern, and the mask pattern is composed of a shielding portion in the shape of the line pattern and a (line-shaped) phase shifter provided within the shielding portion. Also,

when, for example, the first pattern is a line pattern, a third pattern may be present in a direction vertical to the line direction of the first pattern.

In the first photomask, each of regions of the transparent portion disposed on both sides of the second pattern may have a width larger than a given dimension. Alternatively, the second pattern may be isolated. Specifically, in the case where the second pattern is a line pattern, no other pattern may be present in a direction vertical to the line direction of the second pattern. In this case, the third pattern has the mask enhancer structure or is made of a shielding portion. However, the third pattern may be provided with a semi-shielding portion for partially transmitting the exposing light in an identical phase with respect to the transparent portion instead of the shielding portion of the mask enhancer structure.

In the first photomask, the second pattern may be close to a fourth pattern included in the mask pattern at a distance not larger than the given distance with the transparent portion sandwiched therebetween, and the distance between the second pattern and the fourth pattern may be larger than the distance between the first pattern and the third pattern. In this case, each of the third pattern and the fourth pattern has the mask enhancer structure or is made of a shielding portion. However, each of the third pattern and the fourth pattern may be provided with a semi-shielding portion for partially transmitting the exposing light in an identical phase with respect to the transparent portion instead of the shielding portion of the mask enhancer structure.

In the first photomask, the second pattern may be close to a fifth pattern included in the mask pattern at a distance equivalent to (including substantially equivalent to) the distance between the first pattern and the third pattern with the transparent portion sandwiched therebetween, the third pattern may have the mask enhancer structure, and the fifth pattern may be made of a shielding portion. In this case, the third pattern may be

provided with a semi-shielding portion for partially transmitting the exposing light in an identical phase with respect to the transparent portion instead of the shielding portion of the mask enhancer structure.

In the first photomask, the first pattern and the second pattern may be connected to each other, thereby forming one continuous pattern. When, for example, the first and second patterns are line patterns, the first and second patterns may be connected to each other along the line direction.

In the first photomask, when the given distance is not larger than $(\lambda/NA) \times M$, wherein λ indicates a wavelength of the exposing light and M and NA respectively indicate a reduction ratio and numerical aperture of a reduction projection optical system of a projection aligner, the aforementioned effects can be definitely attained.

In the first photomask, when each of the first pattern and the second pattern has a width not larger than $(0.8 \times \lambda/NA) \times M$, wherein λ indicates a wavelength of the exposing light and M and NA respectively indicate a reduction ratio and numerical aperture of a reduction projection optical system of a projection aligner, the aforementioned effects can be definitely attained. In this case, even in the case where desired patterns (for example, resist patterns) to be formed by respectively transferring the first pattern and the second pattern onto a material to be exposed have the same width, the widths of the first pattern and the second pattern should not be always the same. However, a difference in the width between the first pattern and the second pattern is preferably not larger than $(0.2 \times \lambda/NA) \times M$. Thus, even when phase shifters having the same width are provided in the first pattern and the second pattern, sufficient contrast can be attained in the exposure of the respective patterns. In this case, a ratio of the width of the phase shifter of the mask enhancer structure of the first pattern to the width of the first pattern may be smaller than a ratio of the width of the phase shifter of the mask enhancer structure of the second pattern to the

width of the second pattern.

In the first photomask, each of the first pattern and the second pattern may be provided with a semi-shielding portion for partially transmitting the exposing light in an identical phase with respect to the transparent portion instead of the shielding portion of the mask enhancer structure. In this case, the semi-shielding portion transmits the exposing light with a phase difference not less than (-30 + 360 x n) degrees and not more than (30 + 360 x n) degrees (wherein n is an integer) with respect to the transparent portion. In other words, an identical phase herein means a phase difference not less than (-30 + 360 x n) degrees and not more than (30 + 360 x n) degrees. Also, the semi-shielding portion is made of a metal thin film with a thickness of 30 nm or less.

In the first photomask, the phase shifter of the mask enhancer structure of each of the first pattern and the second pattern transmits the exposing light with a phase difference not less than (150 + 360 x n) degrees and not more than (210 + 360 x n) degrees (wherein n is an integer) with respect to the transparent portion. In other words, an opposite phase herein means a phase difference not less than (150 + 360 x n) degrees and not more than (150 + 360 x n) degrees.

In the first photomask, the phase shifter of the mask enhancer structure of each of the first pattern and the second pattern is preferably formed by trenching the transparent substrate.

Thus, transmittance equivalent to that of the transparent substrate (the transparent portion) (i.e., transmittance of substantially 100%) can be realized as the transmittance of the phase shifter.

The second photomask of this invention includes a mask pattern formed on a transparent substrate; and a transparent portion of the transparent substrate where the mask pattern is not formed, and the mask pattern includes a first pattern having a mask enhancer

structure including a phase shifter for transmitting exposing light in an opposite phase with respect to the transparent portion and a shielding portion surrounding the phase shifter and a second pattern adjacent to the first pattern with the transparent portion sandwiched therebetween, and a width of the phase shifter of the mask enhancer structure of the first pattern is set to be smaller as a distance between the first pattern and the second pattern is smaller.

In the second photomask, the width of the phase shifter of the first pattern having the mask enhancer structure is reduced as the distance from the adjacent second pattern is smaller. Therefore, in accordance with the degree at which light (in an identical phase with respect to the transparent portion) rounding to the back side of the first pattern through the transparent portion disposed around the first pattern is reduced owing to the adjacent second pattern, light (in an opposite phase with respect to the transparent portion) passing through the inside of the first pattern (the phase shifter) can be reduced. Accordingly, the shielding property of the first pattern can be sufficiently improved, and hence, an exposure margin is increased and contrast in a light intensity distribution formed in the exposure is improved. In other words, also in a photomask including not only an isolated pattern but also complicated patterns close to one another, the effect to increase a process margin can be sufficiently attained by employing the mask enhancer structure. Also, since the width of the phase shifter of the mask enhancer structure can be optimized in accordance with the close relationship between patterns, a photomask capable of fine pattern formation with random pattern layout can be realized.

The third photomask of this invention includes a mask pattern formed on a transparent substrate; and a transparent portion of the transparent substrate where the mask pattern is not formed, and the mask pattern includes a first pattern having a mask enhancer structure including a phase shifter for transmitting exposing light in an opposite phase with

respect to the transparent portion and a shielding portion surrounding the phase shifter and a second pattern adjacent to the first pattern with the transparent portion sandwiched therebetween, and a width of the phase shifter of the mask enhancer structure of the first pattern is set to be smaller when the second pattern has the mask enhancer structure than when the second pattern is made of a shielding portion.

In the third photomask, the width of the phase shifter of the first pattern having the mask enhancer structure is smaller when the adjacent second pattern has the mask enhancer structure than when the second pattern is made of a shielding portion. In other words, the width of the phase shifter of the first pattern is reduced as the shielding property of the second pattern is higher. Therefore, in accordance with the degree at which light (in an identical phase with respect to the transparent portion) rounding to the back side of the first pattern through the transparent portion disposed around the first pattern is reduced owing to the adjacent second pattern, light (in an opposite phase with respect to the transparent portion) passing through the inside of the first pattern (the phase shifter) can be reduced. Accordingly, the shielding property of the first pattern can be sufficiently improved, and hence, an exposure margin is increased and contrast in a light intensity distribution formed in the exposure is improved. In other words, also in a photomask including not only an isolated pattern but also complicated patterns close to one another, the effect to increase a process margin can be sufficiently attained by employing the mask enhancer structure. Also, since the width of the phase shifter of the mask enhancer structure can be optimized in accordance with the shielding property of the adjacent pattern, a photomask capable of fine pattern formation with random pattern layout can be realized.

The pattern formation method of this invention uses any of the aforementioned photomasks of the invention, and includes the steps of forming a resist film on a substrate; irradiating the resist film with the exposing light through the photomask; and forming a

resist pattern by developing the resist film having been irradiated with the exposing light.

In the pattern formation method of this invention, the same effects as those attained by the aforementioned photomasks of this invention can be attained. Also, oblique incident illumination (off-axis illumination) is preferably employed in the step of irradiating the resist film with the exposing light. Thus, contrast between portions respectively corresponding to the mask pattern and the transparent portion can be improved in a light intensity distribution of light having passed through the photomask. Also, the focus characteristic of the light intensity distribution is improved. Accordingly, an exposure margin and a focus margin are increased in the pattern formation. In other words, fine pattern formation with a good defocus characteristic can be realized. Furthermore, even when patterns having the mask enhancer structure are close to each other on the photomask, the contrast of the respective patterns are largely improved in the exposure.

The mask data generation method of this invention for a photomask including a mask pattern formed on a transparent substrate and a shielding portion of the transparent substrate where the mask pattern is not formed, includes the steps of generating a pattern corresponding to a desired unexposed region of a resist formed by irradiating the resist with exposing light through the photomask; determining a shape of a phase shifter disposed within the pattern for transmitting the exposing light in an opposite phase with respect to the transparent portion; adjusting a width of the phase shifter on the basis of a distance from the pattern to a different pattern close to the pattern with the transparent portion sandwiched therebetween; setting an edge of the pattern corresponding to a boundary with the transparent portion as a CD adjustment edge; predicting a dimension of a resist pattern formed by using the pattern including the phase shifter through simulation; and when the predicted dimension of the resist pattern does not accord with a desired

dimension, deforming the pattern by moving the CD adjustment edge.

In the mask data generation method of this invention, the width of the phase shifter of the mask enhancer structure is adjusted on the basis of a distance from the different close pattern to the pattern having the mask enhancer structure (the target pattern). Therefore, by, for example, reducing the width of the phase shifter as the distance from the different pattern is smaller, light (in an opposite phase with respect to the transparent portion) passing through the inside of the target pattern (the phase shifter) can be reduced in accordance with the degree at which light (in an identical phase with respect to the transparent portion) rounding to the back side of the target pattern through the transparent portion disposed around the target portion is reduced owing to the different pattern. Accordingly, the shielding property of the target pattern can be sufficiently improved, and hence, an exposure margin is increased and contrast in a light intensity distribution formed in the exposure is improved. In other words, also in a photomask including not only an isolated pattern but also complicated patterns close to one another, the effect to increase a process margin can be sufficiently attained by employing the mask enhancer structure. Also, since the width of the phase shifter of the mask enhancer structure can be optimized in accordance with the close relationship between patterns, a photomask capable of fine pattern formation with random pattern layout can be realized.

In the mask data generation method of the invention, the pattern may include a semi-shielding portion for transmitting the exposing light in an identical phase with respect to the transparent portion.

In the mask data generation method of the invention, the step of determining a shape of a phase shifter preferably includes the sub-steps of setting at least two or more different widths as a width of the phase shifter; and setting the width of the phase shifter to be larger when the pattern has a small width not larger than a given width than when the

pattern has a width larger than the given width.

Thus, a process margin in forming an isolated pattern can be increased.

In the mask data generation method of the invention, the step of adjusting a width of the phase shifter preferably includes the sub-steps of setting at least two or more different widths as the width of the phase shifter; and setting the width of the phase shifter to be smaller when the distance between the pattern and the different pattern is not larger than a given dimension than when the distance between the pattern and the different pattern is larger than the given dimension.

Thus, the aforementioned effects of the mask data generation method of this invention can be definitely attained.

In the mask data generation method of the invention, the step of adjusting a width of the phase shifter preferably includes the sub-steps of setting at least two or more different widths as the width of the phase shifter; and setting the width of the phase shifter to be smaller when the pattern is close to the different pattern at a distance not larger than a given dimension and the different pattern includes a different phase shifter than when the pattern is close to the different pattern at a distance not larger than the given dimension and the different pattern does not include a different phase shifter.

Thus, since the width of the phase shifter of the target pattern is reduced as the shielding property of the different pattern is higher, light (in an opposite phase with respect to the transparent portion) passing through the inside of the target pattern (the phase shifter) can be reduced in accordance with the degree at which light (in an identical phase with respect to the transparent portion) rounding to the back side of the target pattern through the transparent portion disposed around the target portion is reduced owing to the different pattern. Accordingly, the aforementioned effects of the mask data generation method of this invention can be definitely attained.

In the mask data generation method of the invention, the different pattern may include two patterns close to respective sides of the pattern, and the step of adjusting a width of the phase shifter may include sub-steps of setting at least two or more different widths as the width of the phase shifter; obtaining distances S1 and S2 respectively from the two patterns close to the respective sides of the pattern to the pattern; and setting the width of the phase shifter to be smaller when (S1 + S2)/2 is not larger than a given value than when (S1 + S2)/2 is larger than the given value. Also in this case, the aforementioned effects of the mask data generation method of this invention can be definitely attained.

As described so far, according to the present invention, the effects to improve contrast in a light intensity distribution and to increase a process margin can be sufficiently attained by employing the mask enhancer structure also in a photomask including not only an isolated pattern but also complicated patterns close to one another. Also, since the width of the phase shifter of the mask enhancer structure can be optimized in accordance with the close relationship between patterns or the shielding property of an adjacent pattern, a photomask capable of fine pattern formation with random pattern layout can be realized.

Brief Description of Drawings

FIG. **1A** is a plan view of a photomask employing a mask enhancer according to the invention, and FIGS. **1B** and **1C** are cross-sectional views taken on line I-I of FIG. **1A**.

FIG. **2** is a plan view of another photomask employing the mask enhancer according to the invention.

FIG. **3A** is a plan view of a photomask according to Embodiment 1 of the invention and FIG. **3B** is a cross-sectional view taken on line II-II of FIG. **3A**.

FIG. **4** is a plan view of another photomask according to Embodiment 1 of the

invention.

FIG. **5** is a plan view of a photomask according to Embodiment 1 in which a semi-shielding portion is used in the mask enhancer structure.

FIG. **6A** is a diagram of an exemplified pattern having the mask enhancer structure of the invention and FIG. **6B** is a contour graph obtained by plotting results of simulation for exposure margins obtained with various combinations of a pattern width **L** and a phase shifter width **F** of the pattern of FIG. **6A**.

FIG. **7A** is a diagram of an exemplified pattern having the mask enhancer structure of the invention and included in densely arranged patterns and FIG. **7B** is a diagram of a light intensity distribution formed in exposure on a wafer in a position corresponding to a line **BB'** of FIG. **7A**.

FIGS. **8A** and **8B** are diagrams for showing results of simulation for dependency of light intensity **Ic** of FIG. **7B** on the phase shifter width **F**.

FIG. **9** is a graph obtained by plotting phase shifter widths **Fopt** for attaining a maximum exposure margin with a close distance **S** between patterns changed on the basis of results of simulation for the exposure margin in formation of a pattern with a width of 70 nm by using the mask pattern of FIG. **7A**.

FIG. **10A** is a diagram of an exemplified pattern having the mask enhancer structure of the invention and included in densely arranged patterns together with another pattern having the mask enhancer structure and FIG. **10B** is a graph obtained by plotting phase shifter widths **Fopt** for attaining a maximum exposure margin with a close distance **S** between patterns changed on the basis of results of simulation for the exposure margin in formation of a pattern with a width of 70 nm by using the mask pattern of FIG. **10A**.

FIG. **11** is a plan view of a photomask according to Modification 1 of Embodiment 1 of the invention.

FIG. **12** is a plan view of a photomask according to Modification 1 of Embodiment 1 of the invention in which a semi-shielding portion is used in the mask enhancer structure.

FIGS. **13A**, **13B**, **13C** and **13D** are diagrams for explaining a method for converting densely arranged patterns composed of patterns arranged at irregular distances into equivalent densely arranged patterns composed of patterns arranged at an equal distance in the photomask of Modification 1 of Embodiment 1.

FIG. **14** is a plan view of a photomask according to Modification 2 of Embodiment 1 of the invention.

FIGS. **15A, 15B, 15C** and **15D** are cross-sectional views for showing procedures in a pattern formation method according to Embodiment 2 of the invention.

FIG. **16A** is a diagram of a general exposure light source, FIG. **16B** is a diagram of an annular exposure light source, FIG. **16C** is a diagram of a quadrupole exposure light source and FIG. **16D** is a diagram of an annular/quadrupole exposure light source.

FIG. **17** is a flowchart for a mask data generation method according to Embodiment 3 of the invention.

FIG. **18A, 18B, 18C, 18D, 18E** and **18F** are diagrams for showing specific mask patterns generated in respective procedures in the mask data generation method of Embodiment 3.

FIGS. **19A, 19B, 19C, 19D** and **19E** are diagrams for explaining a contrast enhancement effect attained by the mask enhancer structure found by the present inventor.

Best Mode for Carrying Out the Invention

Prerequisites

Prerequisites for describing preferred embodiments of the invention will be first

described.

Since a photomask is generally used in a reduction projection type aligner, it is necessary to consider a reduction ratio in arguing a pattern dimension on the mask. However, in order to avoid confusion, in the description of each embodiment below, when a pattern dimension on a mask is mentioned in correspondence to a desired pattern to be formed (such as a resist pattern), a value obtained by converting the pattern dimension by using a reduction ratio is used unless otherwise mentioned. Specifically, also in the case where a resist pattern with a width of 100 nm is formed by using a mask pattern with a width of M x 100 nm in a 1/M reduction projection system, the width of the mask pattern and the width of the resist pattern are both described as 100 nm.

Also, in each embodiment of the invention, **M** and **NA** respectively indicate a reduction ratio and numerical aperture of a reduction projection optical system of an aligner and λ indicates the wavelength of exposing light unless otherwise mentioned.

Moreover, pattern formation is described on the assumption that the positive resist process for forming a resist pattern correspondingly to an unexposed region is employed. In the case where the negative resist process is employed, since a shielded region of a resist is removed, a resist pattern of the positive resist process is replaced with a space pattern.

Moreover, a photomask described in each embodiment is assumed to be a transmission mask. In the case where the photomask is applied to a reflection mask, since a transparent region and a shielding region of a transmission mask respectively correspond to a reflection region and a non-reflection region, the transmission phenomenon is replaced with the reflection phenomenon. Specifically, a transparent portion or a transparent region is replaced with a reflection portion or a reflection region, and a shielding portion is replaced with a non-reflection portion. Furthermore, a region partially transmitting light is replaced with a portion partially reflecting light, and transmittance is replaced with

reflectance.

Mask Enhancer

Next, a mask enhancer described in each embodiment of the invention will be simply explained (see detailed explanation in the aforementioned Literature 1).

FIG. **1A** is a diagram for explaining the mask enhancer (a plan view of a photomask provided with a mask pattern having a mask enhancer structure), and FIGS. **1B** and **1C** are variations of a cross-sectional view taken on line I-I of FIG. **1A**. It is noted that a transparent substrate **100** is perspectively shown in FIG. **1A**.

As shown in FIG. **1A**, mask patterns (patterns **111** and **112**) used for forming desired line-shaped patterns on a wafer through exposure are drawn on the transparent substrate **100**. At this point, each mask pattern is a shielding pattern for forming a shielded region on the wafer in a position corresponding to the mask pattern through the exposure performed by using the photomask. Also, a portion of the transparent substrate **100** in which no mask pattern is formed corresponds to a transparent portion (an opening).

Herein, a line-shaped pattern means a rectangular region with a length (a dimension on the wafer) not smaller than twice of the exposure wavelength (of, for example, 193 nm when the exposing light is Ar excimer laser) and is not limited to a pattern in the shape of a line as a whole. In other words, in an arbitrary pattern including the aforementioned rectangular region, the rectangular region alone is dealt with as a line-shaped pattern. In a light intensity distribution formed in the exposure of a shielding pattern of a line-shaped pattern, in order that a light intensity distribution obtained in the vicinity of the center of the line-shaped pattern having a finite length is equivalent to a light intensity distribution of a line-shaped pattern having an infinite length, the line-shaped pattern having a finite length should have a length not smaller than twice of the exposure wavelength. In other words, a line-shaped pattern having a length not smaller

than twice of the exposure wavelength can be dealt with as a line-shaped pattern having an infinite length.

FIG. **2** shows an example of a pattern including a rectangular region having a length not smaller than twice of the exposure wavelength. In FIG. **2**, like reference numerals are used to refer to like elements used in the photomask of FIG. **1A** so as to omit the description. As shown in FIG. **2**, in a frame-like pattern **113** surrounding transparent portions **104** (more precisely, part of the transparent portions), when there is a partial pattern **113A** (a partial pattern sandwiched between a pair of transparent portions **104**) corresponding to a rectangular region having a length not smaller than twice of the exposure wavelength, the partial pattern **113A** is designated as a line-shaped pattern.

Each of the patterns **111** and **112** corresponding to the mask patterns is composed of a shielding portion **101** alone or a combination of a shielding portion **101** and a phase shifter **102**. The shielding portion **101**, namely, a shielding film, is made of a shielding material, such as Cr, minimally transmitting light. On the other hand, the phase shifter **102** transmits light, and between light passing through the phase shifter **102** and light passing through the transparent portion, there is an opposite phase relationship (specifically, a relationship with a phase difference not less than (150 + 360 x n) degrees and not more than (210 + 360 x n) degrees (wherein n is an integer)). In the following description, a simply mentioned phase shifter has transmittance equivalent to that of a transparent portion unless otherwise mentioned. However, the transmittance of the phase shifter **102** is not limited to 100% but the phase shifter **102** has transmittance at least 20% or more and preferably has high transmittance of 50% or more.

As shown in FIG. **1A**, each of the patterns **111** and **112** is a pattern isolatedly present on the transparent substrate **100**. At this point, being isolatedly present means being affected by none of other patterns in the exposure, and specifically means that none

of the other patterns is present at a distance not larger than 2 x λ/NA corresponding to a distance where the influence of interference can be optically ignored, namely, no other pattern is close.

It is herein determined whether or not a pattern is isolated merely on the basis of a target line-shaped rectangular region. In other words, there is a case where a given pattern is isolated although it is not completely separated from another pattern. Specifically, for example, in the pattern **113** shown in FIG. **2**, when the line-shaped partial pattern **113A** is sandwiched between the transparent portions **104** each with a width larger than the dimension where the influence of the interference can be optically ignored (namely, 2 x λ/NA), the line-shaped partial pattern **113A** is regarded to be isolated.

Furthermore, as shown in FIG. **1A**, the pattern **111** is composed of a partial pattern **111A** with a line width **Ww** larger than a given dimension **W0** (Ww > W0) and a partial pattern **111B** with a line width **L1** not larger than the given width **W0** (W0 ≥ L1). Also, a phase shifter **102** with a line width **F1** is provided at the center of the partial pattern **111B**. In other words, the pattern **111** includes a region corresponding to a shielding portion **101** in the shape of the pattern **111** and a region corresponding to the phase shifter **102** provided in an opening formed within the shielding portion **101**. Moreover, as shown in FIG. **1B**, the shielding portion **101** is made of a shielding film and the phase shifter **102** can be formed by trenching the transparent substrate **100** in the opening of the shielding film. This is the most preferable structure for realizing a phase shifter having transmittance equivalent to that of the transparent portion. When such a phase shifter having sufficiently high transmittance is used, parameters indicating satisfactoriness of the pattern formation characteristics, such as an exposure margin and a depth of focus, can be largely improved. However, the cross-sectional structure for providing the phase shifter **102** at the center of the shielding portion **101** is not limited to that shown in FIG. **1B**. It is

hereinafter assumed, unless otherwise mentioned, that the outermost region of each pattern used as a mask pattern is made of a shielding portion and that the line width of each pattern is defined as a distance from a boundary between one end of the shielding portion of the outermost region and a transparent portion to a boundary between the other end of the shielding portion of the outermost region and the transparent portion, namely, as the width of the whole pattern.

In general, it is experimentally known that a dimension where light rounding the periphery of a mask pattern through diffraction cannot be ignored is approximately 0.8 x λ/NA. Accordingly, when a mask pattern with a width not smaller than 0.8 x λ/NA is made of a shielding portion alone, a sufficiently high shielding property can be realized, and hence, high contrast can be attained in a light intensity distribution formed in the exposure. However, in the case where a mask pattern having a width not larger than 0.8 x λ/NA is made of a shielding portion alone, a sufficient shielding property cannot be attained due to diffracted light rounding beneath the mask pattern through a transparent portion disposed around the mask pattern, and as a result, contrast in a light intensity distribution formed in the exposure is lowered.

At this point, when light in the relationship of an opposite phase with the diffracted light rounding through the transparent portion can be set to pass through the center of the mask pattern, these lights interfere with each other so as to be mutually cancelled. Accordingly, when a phase shifter is provided at the center of the mask pattern (i.e., the shielding pattern) with a width not larger than 0.8 x λ/NA, the shielding property can be improved, resulting in realizing high contrast in the formation of the pattern with a fine line width. This is the principal of the mask enhancer, and the structure in which a phase shifter is provided at the center of a shielding pattern having a width not larger than 0.8 x λ/NA is designated as the mask enhancer structure. However, when a phase shifter

is provided at the center of a mask pattern formed as a shielding portion having a width exceeding 0.8 x λ/NA, the shielding property is lowered on the contrary. This is for the following reason: In the case where diffracted light rounding the periphery of a mask pattern is minimally present, when light in the relationship of the opposite phase with the diffracted light passes through the mask pattern, the light in the opposite phase is excessive in the event.

Furthermore, although the upper limit of the dimension where the shielding property of a shielding pattern can be improved by providing a phase shifter at the center of the shielding pattern is 0.8 x λ/NA, a dimension where the shielding property of a shielding pattern can be remarkably improved by providing a phase shifter is 0.6 x λ/NA or less.

As described above, in order to realize a photomask capable of fine pattern formation by employing the mask enhancer structure, the aforementioned given dimension **W0** should be 0.8 x λ/NA or less and is more preferably 0.6 x λ/NA or less. Also, since a dimension where the pattern formation using a shielding pattern is very difficult due to the diffraction is 0.3 x λ/NA, the given dimension **W0** is preferably 0.3 x λ/NA or more.

Furthermore, as shown in FIG. **1A**, the pattern **112** is composed of a partial pattern **112A** with a line width **L2** not larger than the given dimension **W0** ($W0 \geq L2$) and a partial pattern **112B** with a line width **L3** not larger than the given dimension **W0** ($W0 \geq L3$). Also, similarly to the pattern **111**, the pattern **112** includes a region corresponding to a shielding portion (shielding film) **101** in the shape of the pattern **112** and a region corresponding to a phase shifter **102** provided in an opening of the shielding portion **101**. Moreover, a phase shifter **102A** with a line width **F2** is provided at the center of the partial pattern **112A**, and a phase shifter **102B** with a line width **F3** is provided at the center of the partial pattern **112B**. In other words, each of the partial patterns **112A** and **112B** has the

mask enhancer structure. At this point, among the pattern widths **L2** and **L3** of the partial patterns **112A** and **112B** and a given dimension **W1**, there is a relationship of $W0 \geq L2 > W1 \geq L3$. Between the line widths **F2** and **F3** of the phase shifters **102A** and **102B**, there is a relationship of $F3 > F2$.

In general, the diffracted light rounding to the back side of a mask pattern through a transparent portion disposed around the mask pattern due to the diffraction is increased as the line width of the mask pattern is reduced. Accordingly, in the mask enhancer structure, as the line width of a mask pattern is reduced, the width of a phase shifter used for canceling the light rounding to the back side of the mask pattern due to the diffraction is preferably increased. In this manner, also in a mask pattern composed of a plurality of partial patterns with different line widths, all the partial patterns can attain a high shielding property, resulting in realizing a photomask that can attain high contrast in a light intensity distribution formed in the exposure. In this case, although a plurality of partial patterns with different line widths included in one pattern are exemplified, a similar architecture (in which the width of a phase shifter is increased as the line width of a pattern is reduced) is preferably employed for a plurality of different patterns formed isolatedly on one transparent substrate. Specifically, in the architecture shown in FIG. **1A**, in the case where there is a relationship of $W0 \geq L1 > W1 \geq L3$ between the line width **L1** of the partial pattern **111B** of the pattern **111** and the line width **L3** of the partial pattern **112B** of the pattern **112**, there is a relationship of $F3 > F1$ between the line width **F1** of the phase shifter **102** of the partial pattern **111B** and the line width **F3** of the phase shifter **102B** of the partial pattern **112B**.

In the case where a difference in the line width between respective patterns is so small that a difference in the intensity of the diffracted lights rounding the peripheries of the respective patterns can be ignored, phase shifters provided at the centers of the

respective patterns may have the same width. Specifically, in the architecture shown in FIG. **1A**, in the case where there are relationships of $W0 \geq L1 > W1$ and $W0 \geq L2 > W1$ between the line width **L1** of the partial pattern **111B** of the pattern **111** and the line width **L2** of the partial pattern **112A** of the pattern **112**, there may be a relationship of $F2 = F1$ between the line width **F1** of the phase shifter **102** of the partial pattern **111B** and the line width **F2** of the phase shifter **102A** of the partial pattern **112A**.

As described so far, when the mask enhancer structure is employed in mask patterns isolatedly present, all the isolated mask patterns can attain a high shielding property, and therefore, a photomask that can attain a light intensity distribution with high contrast can be realized. In other words, a photomask good at fine pattern formation can be realized.

Although the mask enhancer structure is composed of a shielding film such as a Cr film and a phase shifter in the above description, a similar effect can be attained even when a shielding portion **101** made of a shielding film is replaced with a semi-shielding portion **103** made of a semi-shielding film as shown in FIG. **1C**. A difference between FIG. **1B** and FIG. **1C** is the replacement of the shielding portion (the shielding film) **101** for the semi-shielding portion (the semi-shielding film) **103**. The semi-shielding portion **103** partially transmits the exposing light in an identical phase with respect to the transparent portion. Specifically, there is an identical phase relationship (specifically, a relationship with a phase difference not less than (-30 + 360 x n) degrees and not more than (30 + 360 x n) degrees (wherein n is an integer)) between light passing through the semi-shielding portion **103** and light passing through the transparent portion, whereas the semi-shielding portion **103** preferably has transmittance of 15% or less. In this manner, the light passing through the mask pattern can be prevented from being too excessive to expose a resist. As the semi-shielding film used to form such a semi-shielding portion **103**, a metal thin

film with a thickness of, for example, 30 nm or less can be used. The metal thin film can be a thin film (with a thickness of 30 nm or less) made of any of metals such as chromium (Cr), tantalum (Ta), zirconium (Zr), molybdenum (Mo) and titanium (Ti) or an alloy of any of these metals. Specific examples of the alloy are Ta-Cr alloy, Zr-Si alloy, Mo-Si alloy and Ti-Si alloy.

Furthermore, when the semi-shielding portion **103** is used instead of the shielding portion **101** as described above, the shielding property of a mask pattern with a line width exceeding 0.8 x λ/NA can be improved by employing the mask enhancer structure. This is for the following reason: Since light passing through a mask pattern with a width exceeding 0.8 x λ/NA is in the identical phase to light passing through the transparent portion, light in the opposite phase can be prevented from being excessive by providing a phase shifter within the pattern. However, the effect attained when the semi-shielding portion **103** is used in a mask pattern having a line width not larger than 0.8 x λ/NA is completely the same as the effect attained by using the shielding portion **101**.

In each of embodiments described below, the architecture of a mask enhancer structure employed when a mask pattern to be applied for the mask enhancer structure is close to another pattern will be described.

EMBODIMENT 1

A photomask according to Embodiment 1 of the invention will now be described with reference to the accompanying drawings.

FIG. **3A** is a plan view of the photomask of Embodiment 1 and FIG. **3B** is a cross-sectional view taken on line II-II of FIG. **3A**. It is noted that a transparent substrate **100** is perspectively shown in FIG. **3A**.

As shown in FIG. **3A**, mask patterns (line patterns **121** through **123**) used for forming desired line-shaped patterns on a wafer through exposure are drawn on the

transparent substrate **100**. At this point, each of the line patterns **121** through **123** is basically made of a shielding portion **101**. Also, in a central portion of a pattern region with a line width not larger than a given dimension **W0** in each of the line patterns **121** through **123**, the shielding portion **101** has an opening in which a phase shifter **102** is provided. In other words, each of the line patterns **121** through **123** has the mask enhancer structure. For example, the pattern **121** is a pattern with a line width **L4** satisfying a relationship of W2 ≥ L4 > W3 wherein **W2** and **W3** are given dimensions satisfying a relationship of W0 ≥ W2 > W3, and a phase shifter **102** is provided at the center of the pattern **121**.

Also, as shown in FIG. **3A,** the pattern **121** is composed of a partial pattern **121A** close to the other patterns **122** and **123** at a distance not larger than a given distance **S0** with a transparent portion sandwiched therebetween along a direction vertical to the line direction thereof and a partial pattern **121B** not close to another pattern at a distance not larger than the given distance **S0** along the vertical direction (i.e., being isolated). It is noted that the partial pattern **121A** and the patterns **122** and **123** sandwiching the partial pattern **121A** together form densely arranged patterns **151**. Also, a phase shifter **102A** with a line width **F4A** is provided at the center of the partial pattern **121A** and a phase shifter **102B** with a line width **F4B** is provided at the center of the partial pattern **121B.** In other words, each of the partial patterns **121A** and **121B** has the mask enhancer structure. At this point, the phase shifter **102A** of the partial pattern **121A** included in the densely arranged patterns **151** has a smaller width than the phase shifter **102B** of the isolated partial pattern **121B,** namely, F4B > F4A.

In the above description of the densely arranged patterns, another pattern close to a target line-shaped pattern is a different pattern separated from the target line-shaped pattern. However, the densely arranged patterns are not necessarily composed of different

patterns separated from one another. Specifically, if, for example, a plurality of line-shaped rectangular regions belonging to one pattern are arranged with a transparent portion sandwiched among them, the plural line-shaped rectangular regions alone may be specifically dealt with to be designated as line-shaped densely arranged patterns. FIG. **4** shows an example of a pattern including such plural line-shaped rectangular regions. In FIG. **4**, like reference numerals are used to refer to like elements of the photomask of FIG. **3A** so as to omit the description. As shown in FIG. **4**, in a pattern **120** including a plurality of line-shaped rectangular regions, the plural line-shaped rectangular regions close to one another with a transparent portion having a width not larger than the given distance **S0** sandwiched therebetween together form densely arranged patterns **120C**. Specifically, the width **F4A** of a phase shifter **102** provided in a partial pattern **120A**, that is, a rectangular region disposed at the center of the plural rectangular regions included in the densely arranged patterns **120C**, is smaller than the width **F4B** of a phase shifter **102** provided in a partial pattern **120B**, that is, an isolated rectangular region. Also, the width of a phase shifter **102** provided in each rectangular region disposed on a side of the partial pattern **120A** is larger than the width **F4A** and not larger than the width **F4B**. Furthermore, the transparent portion (sandwiched between the plural line-shaped rectangular regions) may be a transparent portion surrounded with the shielding portion **101** such as the transparent portion of the frame-like pattern **113** shown in FIG. **2**.

Furthermore, as shown in FIG. **3B**, the shielding portion **101** is made of a shielding film and the phase shifter **102** can be formed by trenching a portion of the transparent substrate **100** in the opening of the shielding film.

According to Embodiment 1, in the mask enhancer structure of the partial pattern **121A** close to the other patterns **122** and **123** at a distance not larger than the given distance, the width of the phase shifter **102** (the phase shifter **102A**) is made relatively

small. Therefore, in accordance with the degree at which light (in an identical phase with respect to the transparent portion) rounding to the back side of the partial pattern **121A** through the transparent portion disposed around the partial pattern **121A** is reduced owing to the close patterns **122** and **123**, light (in an opposite phase with respect to the transparent portion) passing through the inside of the partial pattern **121A** (the phase shifter **102A**) can be reduced. Accordingly, the shielding property of the partial pattern **121A** can be sufficiently improved, and hence, an exposure margin is increased and contrast in a light intensity distribution formed in the exposure is improved. In other words, also in a photomask including not only an isolated pattern but also complicated patterns close to each other, the effect to increase the process margin can be sufficiently attained by employing the mask enhancer structure. Also, since the width of the phase shifter included in the mask enhancer structure can be optimized in accordance with the close relationship between the patterns, a photomask capable of fine pattern formation with random pattern layout can be realized.

Furthermore, according to Embodiment 1, with respect to a pattern having the mask enhancer structure and included in the densely arranged patterns composed of a plurality of patterns arranged at arbitrary distances, a photomask capable of maximizing an exposure margin can be realized. Accordingly, good pattern formation characteristics attained by the mask enhancer structure of a fine mask pattern can be exhibited even when respective mask patterns are in an arbitrary close relationship, and hence, a photomask capable of fine pattern formation can be realized.

In this embodiment, the patterns **122** and **123** close to the pattern **121** having the mask enhancer structure are also shown as patterns having the mask enhancer structure in FIG. 3A. However, the patterns **122** and **123** forming the densely arranged patterns **151** together with the partial pattern **121A** are not limited to the patterns having the mask

enhancer structure but may be patterns made of a shielding portion alone.

Furthermore, although the mask enhancer structure is described as a structure composed of a shielding portion and a phase shifter in this embodiment, the shielding portion may be replaced with a semi-shielding portion. Specifically, as shown in FIG. **5**, the mask enhancer structure of each of the patterns **121** through **123** may be composed of a phase shifter **102** and a semi-shielding portion **103**. As is obvious in FIG. **5**, the shielding portion **101** of FIG. **3A** is replaced with the semi-shielding portion **103**.

Moreover, the partial patterns **121A** and **121B** included in the pattern **121** both have the line width **L4** in this embodiment. However, the line widths of the partial patterns **121A** and **121B** may be different as far as they are larger than the given dimension **W3** and not larger than the given dimension **W2**. Specifically, when the partial pattern **121A** has a line width **L4A** and the partial pattern **121B** has a line width **L4B**, there may be a relationship of $L4A \neq L4B$ as far as $W2 \geq L4A > W3$ and $W2 \geq L4B > W3$. Also, the given dimensions **W2** and **W3** preferably satisfy a relationship of $(W2 - W3) \leq 0.2 \times \lambda/NA$. In other words, a difference between the line width **L4A** of the partial pattern **121A** and the line width **L4B** of the partial pattern **121B** is preferably not larger than $(0.2 \times \lambda/NA) \times M$.

Furthermore, in this embodiment, the partial pattern **121A** included in the densely arranged patterns **151** and the partial pattern **121B** isolated (along the direction vertical to the line direction) are both included in one continuous pattern, i.e., the pattern **121**. However, as far as the aforementioned relationships among the line widths are satisfied, a pattern included in densely arranged patterns and an isolated pattern may be different patterns formed on one transparent substrate.

In this embodiment, the given dimension **W0** is preferably not larger than $0.8 \times \lambda/NA$ and more preferably not smaller than $0.3 \times \lambda/NA$ and not larger than $0.6 \times \lambda/NA$.

In this embodiment, the given distance **S0** is preferably not larger than λ/NA.

Now, it is described in detail based on simulation results that the photomask of this embodiment exhibits good fine pattern formation characteristics not only in an isolated pattern region but also in a densely arranged pattern region owing to the mask enhancer structure.

First, an allowable range of the line width of a mask pattern for attaining sufficient contrast when the width of a phase shifter of the mask enhancer structure is the same will be described. Specifically, a difference between the given dimension **W2** and the given dimension **W3** (W2 – W3) of this embodiment is preferably not larger than 0.2 x λ/NA. This will now be described with reference to the accompanying drawings.

FIG. **6A** is a diagram of an example of a pattern having the mask enhancer structure. The pattern of FIG. **6A** is a line pattern with a pattern width **L** in which a phase shifter **102** with a line width **F** is surrounded with a shielding portion **101**. The present inventor performed optical simulation for formation of a line pattern (a resist pattern) with a width of 70 nm by using the mask pattern of FIG. **6A** with the combination of the width **L** and the width **F** variously varied. In the simulation, the exposure wavelength λ was set to 193 nm and the numerical aperture **NA** was set to 0.75, and 3/4 annular illumination having the outer diameter with a degree of interference of 0.8 and the inner diameter with a degree of interference of 0.6 was used.

FIG. **6B** is a contour graph obtained by plotting exposure margins against various combinations of the widths **L** and **F** in the pattern of FIG. **6A** obtained through the simulation. The contour graph of FIG. **6B** shows a ratio of an exposure margin **E(L,F)** attained in each combination of the widths **L** and **F** to the maximum exposure margin **Emax** attained in a combination of the widths **L** and **F**. Specifically, it shows a contour graph of E(L,F)/Emax. In this graph, the ordinate indicates the width **F** and the abscissa

indicates a value obtained by normalizing (L – F) by λ/NA. It is noted that the exposure margin means a ratio (in %) of exposure energy change necessary for changing a pattern dimension by 10%. Specifically, as the exposure margin is larger, the pattern dimension is more stabilized against the exposure energy change, and hence it is possible to attain a preferable state that the pattern dimension is minimally changed against the exposure energy change in actual pattern formation.

It is understood from the contour graph of FIG. **6B** that in the case where the width **F** is, for example, 60 nm, an exposure margin corresponding to 90% or more of the maximum exposure margin is realized when (L – F) falls in a range from 0.1 x λ/NA to 0.3 x λ/NA. In other words, when the range where an exposure margin corresponding to 90% or more of the maximum exposure margin is realized is regarded as the range for attaining a sufficient exposure margin, the allowable range of the pattern width **L** for obtaining the sufficient exposure margin by using the phase shifter with the width **F** of 60 nm is from F + 0.1 x λ/NA to F + 0.3 x λ/NA.

It is also understood from the graph of FIG. **6B** that the pattern width **L** for attaining the sufficient exposure margin has a range of approximately 0.2 x λ/NA when the width **F** has any value ranging from 40 to 80 nm. In other words, even when phase shifters having the same line width **F** are provided in respective patterns with line widths **L** different by 0.2 x λ/NA or less, the sufficient exposure margin can be attained.

Next, the merit attained by setting the width of a phase shifter provided in the vicinity of the center of a pattern having the mask enhancer structure and included in densely arranged patterns to be smaller than the width of a phase shifter provided in the vicinity of the center of an isolated pattern having the mask enhancer structure will be described with reference to the accompanying drawings.

FIG. **7A** is a diagram of a pattern having the mask enhancer structure and included

in densely arranged patterns. As shown in FIG. **7A**, line-shaped patterns **311** and **312** each made of a shielding portion and having a line width **Lw** are disposed on both sides of and close to a line-shaped pattern **310** with a line width **L** having the mask enhancer structure at a distance **S** (corresponding to a transparent portion). The mask enhancer structure of the line-shaped pattern **310** is constructed by surrounding a phase shifter **310B** with a line width **F** with a shielding portion **310A**.

FIG. **7B** is a diagram of a light intensity distribution formed in exposure on a wafer in a position corresponding to line **BB'** of FIG. **7A**. In FIG. **7B**, when the light intensity obtained at the center of the pattern **310** with a line width **L** is indicated by **Ic** (which is changed depending upon the distance S), a smaller value of the light intensity **Lc** means that the pattern **310** exhibits a higher shielding property. On the contrary, a large value of the light intensity **Lc** means that the pattern **310** cannot sufficiently shield light. It is noted that the light intensity is herein expressed as relative light intensity obtained by assuming the light intensity of the exposing light to be 1 unless otherwise mentioned.

FIGS. **8A** and **8B** show results of simulation for dependency of the light intensity **Ic** on the width **F** of the phase shifter. In the simulation, the exposure wavelength **λ** was set to 193 nm and the numerical aperture **NA** was set to 0.75, and 3/4 annular illumination having the outer diameter with a degree of interference of 0.8 and the inner diameter with a degree of interference of 0.6 was used. Also, the width **L** was set to 100 nm and the width **Lw** was set to 300 nm in the simulation. In other words, the pattern **310** having the width **L** of 100 nm that cannot sufficiently shield light by using a simple shielding pattern (because the width **L** of 100 nm is smaller than $0.8 \times \lambda/NA \approx 206$ nm) has the mask enhancer structure, and the patterns **311** and **312** each having the width **Lw** of 300 nm that can sufficiently shield light by using a simple shielding pattern are made of a shielding portion alone.

FIG. **8A** is a graph of the results of the simulation for the dependency of the light intensity **Ic** on the width **F** of the phase shifter obtained in the case where the distance **S** is substantially infinite, namely, in the case where the pattern **310** having the mask enhancer structure is isolatedly present. Also, FIG. **8B** is a graph of the results of the simulation for the dependency of the light intensity **Ic** on the width **F** of the phase shifter obtained in the case where the distance **S** is 100 nm, namely, in the case where other patterns (the patterns **311** and **312**) are present in the vicinity of the pattern **310** having the mask enhancer structure.

In the graph of FIG. **8A**, the light intensity **Ic** has the minimum value when the width **F** is 65 nm. In other words, it is understood that the maximum shielding property is attained when the width **F** of the phase shifter is 65 nm in the isolated pattern having the mask enhancer structure. On the other hand, in the graph of FIG. **8B**, the light intensity **Ic** has the minimum value when the width **F** is 40 nm. In other words, it is understood that the maximum shielding property is attained when the width **F** is 40 nm in the pattern having the mask enhancer structure and close to other shielding patterns.

In this manner, even when the patterns having the mask enhancer structure have the same line width (**L** = 100 nm), the width of the phase shifter for attaining the maximum shielding property, namely, the width of the phase shifter for attaining the maximum exposure margin, is different depending upon whether the pattern is isolated or included in densely arranged patterns. Specifically, the width of the phase shifter of 40 nm for attaining the maximum exposure margin in the pattern included in the densely arranged patterns is smaller than the width of the phase shifter of 65 nm for attaining the maximum exposure margin in the isolated pattern. This is for the following reason:

In the mask enhancer structure, the diffracted light rounding the periphery of the pattern to the back side of the pattern is cancelled by light in an opposite phase passing

through the inside of the pattern, so as to improve the shielding property. Therefore, as the light rounding the periphery of the pattern is increased, the light in the opposite phase passing through the inside of the pattern is preferably increased. However, when the light rounding the periphery of the pattern is reduced, the light in the opposite phase passing through the inside of the pattern is preferably reduced. This is because if the light in the opposite phase passing through the inside of the mask pattern is excessive, the shielding property of the mask pattern is degraded, resulting in an undesirable condition for the pattern formation.

In the case where a fine shielding pattern is isolatedly present, not only the line width of the pattern is small but also a sufficiently large transparent region is present around the pattern. Therefore, a larger quantity of diffracted light rounds to the back side of the pattern. Accordingly, in order to sufficiently cancel such diffracted light, the mask enhancer structure preferably includes a phase shifter with a large width.

On the other hand, even in a similar fine shielding pattern, when it is close to another shielding pattern, by which the area of a transparent region around the pattern is reduced, the quantity of diffracted light rounding to the back side of the pattern is reduced as compared with that in the isolated pattern. Accordingly, in such a case, the mask enhancer structure preferably includes a phase shifter with a smaller width than in the isolated pattern.

In general, there is a correlation between the shielding property and the exposure margin, the contrast or the like, and therefore, in patterns having the mask enhancer structure and the same line width, a thin phase shifter is preferably provided when the pattern is included in densely arranged patterns together with other patterns and a thick phase shifter is preferably provided when the pattern is isolated. Thus, high pattern formation characteristics can be attained. Now, results of simulation performed for

directly confirming this effect will be described. In this case, the pattern formation characteristics are evaluated on the basis of the exposure margin.

First, the present inventor obtained, through the simulation, the exposure margin obtained in forming a pattern with a width of 70 nm by using the mask pattern of FIG. **7A**. In the simulation, the exposure wavelength λ was set to 193 nm and the numerical aperture **NA** was set to 0.75, and 3/4 annular illumination having the outer diameter with a degree of interference of 0.8 and the inner diameter with a degree of interference of 0.6 was used. Also, the width **L** of the pattern **310** of FIG. **7A** was set to 100 nm and the width **Lw** of the shielding patterns **311** and **312** close to the pattern **310** was set to 300 nm.

FIG. **9** is a graph obtained by plotting the widths **Fopt** of the phase shifter for attaining the maximum exposure margin with the distance **S** between the patterns changed in the aforementioned conditions. In FIG. **9**, the distance **S** is indicated as a value normalized by λ/NA.

As is understood from FIG. **9**, when the distance **S** is not larger than λ/NA (namely, when the normalized distance **S** is not larger than 1), the width **Fopt** of the phase shifter for attaining the maximum exposure margin is reduced. In particular, when the distance **S** is not larger than 0.5 x λ/NA, the optimal width **Fopt** of the phase shifter is reduced to be approximately a half of that obtained when the distance **S** exceeds λ/NA (namely, when the pattern **310** is substantially isolated). Accordingly, it is understood that in order to realize a satisfactory exposure margin, the phase shifter provided at the center of the pattern having the mask enhancer structure and included in the densely arranged patterns composed of patterns arranged at the distance **S** not larger than λ/NA preferably has a smaller width than a phase shifter provided in an isolated pattern. Furthermore, the essence of this preferable architecture is that the ratio of the width of a phase shifter to the line width of a mask pattern included in densely arranged patterns is relatively reduced.

Even when the widths of desired patterns formed on a wafer are the same, the width of a mask pattern may be changed in accordance with a distance to another close pattern due to a phenomenon generally designated as a proximity effect. In this manner, in the case where the line widths of mask patterns are different between a densely arranged pattern region and an isolated pattern region even through the widths of desired patterns formed on a wafer are the same, the ratio of the width of the phase shifter to the width of the mask pattern is appropriately relatively reduced in the densely arranged pattern region.

Specifically, a ratio **Fd/Ld** between the line width **Ld** of a pattern having the mask enhancer structure and disposed in a densely arranged pattern region and the width **Fd** of a phase shifter provided in the vicinity of the center of this pattern is preferably smaller than a ratio **Fi/Li** between the line width **Li** of a pattern having the mask enhancer structure and disposed in an isolated pattern region and the width **Fi** of a phase shifter provided in the vicinity of this pattern.

Furthermore, when the graph of FIG. **9** is observed in detail, it is understood that in the case where the distance **S** is not larger than λ/NA, the width **Fopt** of the phase shifter for attaining the maximum exposure margin is also reduced in proportion to the degree of reduction of the distance **S**. A preferable architecture of a pattern having the mask enhancer structure and included in densely arranged patterns obtained on the basis of this result will be described in detail in Modification 1 below.

In calculation of the width **Fopt** of the phase shifter for attaining the maximum exposure margin shown in FIG. **9**, the width **Fopt** was calculated by assuming that the other patterns (the patterns **311** and **312** of FIG. **7A**) close to the pattern having the mask enhancer structure (the pattern **310** of FIG. **7A**) are simple shielding patterns made of a shielding portion alone, and the calculation results of the widths **Fopt** obtained by assuming that the other close patterns have the mask enhancer structure will now be

described.

FIG. **10A** is a diagram of densely arranged patterns formed by a pattern having the mask enhancer structure together with other patterns having the mask enhancer structure. As shown in FIG. **10A**, line-shaped patterns **321** and **322** with a line width **L** having the mask enhancer structure are disposed on both sides of and close to a line-shaped pattern **320** with a line width **L** having the mask enhancer structure at a distance **S** (corresponding to a transparent region). The mask enhancer structure of each of the patterns **320** through **322** is constructed by surrounding each of phase shifters **320B** through **322B** with a line width **F** with each of shielding portions **320A** through **322A**.

The present inventor obtained, through the simulation, the exposure margin obtained in forming a pattern with a width of 70 nm by using the mask pattern of FIG. **10A**. In the simulation, the exposure wavelength λ was set to 193 nm and the numerical aperture **NA** was set to 0.75, and 3/4 annular illumination having the outer diameter with a degree of interference of 0.8 and the inner diameter with a degree of interference of 0.6 was used. Also, the width **L** of the patterns **320** through **322** of FIG. **10A** was set to 100 nm.

FIG. **10B** is a graph obtained by plotting the widths **Fopt** of the phase shifter for attaining the maximum exposure margin with the distance **S** between the patterns changed in the aforementioned conditions. In FIG. **10B**, the distance **S** is indicated as a value normalized by λ/NA.

As is understood from FIG. **10B**, substantially the same results as those of FIG. **9** are obtained in using the mask pattern shown in FIG. **10A**. Specifically, when the distance **S** is not larger than λ/NA, the width **Fopt** of the phase shifter for attaining the maximum exposure margin is reduced. However, a small difference of the graph of FIG. **10B** from the graph of FIG. **9** is that the width **Fopt** of the phase shifter for attaining the maximum exposure margin is smaller by approximately 5 nm when the distance **S** is the

same. This difference is caused because the light in the opposite phase is excessive as a whole due to the influence of the light in the opposite phase passing through the phase shifters **321B** and **322B** of the other close patterns **321** and **322**. Accordingly, in determining the width of a phase shifter of the mask enhancer structure, even in the case where patterns are close to one another at the same distance, it is preferably grasped whether another pattern close to a target pattern has the mask enhancer structure or is a simple shielding pattern (this preferable architecture will be described in detail in Modification 2 below).

MODIFICATION 1 OF EMBODIMENT 1

A photomask according to Modification 1 of Embodiment 1 of the invention will now be described with reference to the accompanying drawings.

FIG. **11** is a plan view of the photomask of Modification 1 of Embodiment 1, and more specifically, a photomask provided with a mask pattern having the mask enhancer structure and included in densely arranged patterns. In FIG. **11**, a transparent substrate **100** is perspectively shown.

As shown in FIG. **11**, mask patterns (line patterns **124** through **128**) for forming desired line-shaped patterns on a wafer through exposure are drawn on the transparent substrate **100**. In this case, each of the line patterns **124** through **128** is basically made of a shielding portion **101**. Furthermore, a phase shifter **102** is provided at the center of a pattern region of each of the line patterns **124** through **128** having a line width not larger than a given dimension **W0**. Specifically, each of the line patterns **124** through **128** has the mask enhancer structure. For example, the pattern **124** is a pattern with a line width **L5** satisfying a relationship of $W2 \geq L5 > W3$ with respect to given dimensions **W2** and **W3** satisfying a relationship of $W0 \geq W2 > W3$, and the phase shifter **102** is provided at the center of the pattern **124**.

Also, as shown in FIG. **11**, the pattern **124** includes a partial pattern **124A** close to different patterns **125** and **126** at a distance **G1** (S0 > G1) with a transparent portion sandwiched therebetween along a direction vertical to the line direction thereof. The partial pattern **124A** forms densely arranged patterns **152** together with the different patterns **125** and **126** sandwiching the partial pattern **124A**. Also, a phase shifter **102A** with a line width **F5A** is provided at the center of the partial pattern **124A**.

Furthermore, the pattern **124** includes a partial pattern **124B** close to different patterns **127** and **128** at a distance **G2** (S0 > G2 > G1) with the transparent portion sandwiched therebetween along the vertical direction. The partial pattern **124B** forms densely arranged patterns **153** together with the different patterns **127** and **128** sandwiching the partial pattern **124B**. Also, a phase shifter **102B** with a line width **F5B** is provided at the center of the partial pattern **124B**.

This modification is characterized by the architecture in which F5B > F5A. Specifically, in patterns having the mask enhancer structure and included in densely arranged patterns, the width of a phase shifter provided at the center of a pattern included in densely arranged patterns with a high close degree is smaller than the width of a phase shifter provided at the center of a pattern included in densely arranged patterns with a low close degree.

Furthermore, the width of a phase shifter of the mask enhancer structure is preferably smaller in proportion to the close degree of densely arranged patterns including the phase shifter. Specifically, in the mask architecture shown in FIG. **11**, a value (F5B – F5A) is preferably in proportion to a value (G2 – G1).

In the above description, the respective line-shaped patterns are different patterns separated from one another. Also in this modification, however, in the case where a plurality of line-shaped rectangular regions belonging to a complicated polygonal pattern

are regarded as a target, the aforementioned relationships may be satisfied in the respective line-shaped rectangular regions alone as in Embodiment 1. Also, the transparent portion between the line-shaped rectangular regions may be a transparent portion surrounded with the shielding portion **101** such as the transparent portion disposed within the frame-like pattern **113** shown in FIG. **2**.

According to this modification, as the distance to another close pattern is smaller, the width of a phase shifter provided in a pattern having the mask enhancer structure (the pattern **124**) is smaller. Therefore, in accordance with the degree at which light (in an identical phase with respect to the transparent portion) rounding through the transparent portion disposed around the pattern **124** to the back side of the pattern **124** is reduced owing to another close pattern, light (in an opposite phase with respect to the transparent portion) passing through the inside of the pattern **124** (the phase shifter **102**) can be reduced. Accordingly, the shielding property of the pattern **124** can be sufficiently improved, and hence, the exposure margin is increased and the contrast in the light intensity distribution formed in the exposure is improved. In other words, also in a photomask including not only isolated patterns but also complicated patterns close to one another, the effect to increase the process margin can be sufficiently attained by employing the mask enhancer structure. Also, since the width of a phase shifter used in the mask enhancer structure can be optimized in accordance with the close relationship between patterns, a photomask capable of fine pattern formation with random pattern layout can be realized.

Moreover, according to this modification, with respect to a pattern having the mask enhancer structure and included in densely arranged patterns composed of a plurality of patterns arranged at arbitrary distances, a photomask capable of maximizing the exposure margin can be realized. Accordingly, the good pattern formation characteristics

attained owing to the mask enhancer structure employed in fine mask patterns can be exhibited also when respective patterns used as the mask patterns have an arbitrary close relationship, and therefore, a photomask capable of fine pattern formation can be realized.

In this modification, the patterns **125** through **128** close to the pattern **124** having the mask enhancer structure are shown in FIG. **11** also as patterns having the mask enhancer structure. However, the patterns **125** through **128** are not limited to the patterns having the mask enhancer structure but may be patterns made of a shielding portion alone.

Furthermore, although the mask enhancer structure is described to be composed of a shielding portion and a phase shifter in this modification, the shielding portion may be replaced with a semi-shielding portion. Specifically, the mask enhancer structure of each of the patterns **124** through **128** may be composed of a phase shifter **102** and a semi-shielding portion **103** as shown in FIG. **12**. As is obvious from FIG. **12**, the shielding portion **101** of FIG. **11** is replaced with a semi-shielding portion **103**.

Moreover, in this modification, both of the partial pattern **124A** and the partial pattern **124B** included in the pattern **124** have the line width **L5**. However, the line widths of the partial patterns **124A** and **124B** may be different as far as they are larger than the dimension **W3** and not larger than the dimension **W2**. Specifically, assuming that the partial pattern **124A** has a line width **L5A** and the partial pattern **124B** has a line width **L5B**, there may be a relationship of $L5A \neq L5B$ as far as $W2 \geq L5A > W3$ and $W2 \geq L5B > W3$. Also, the given dimensions **W2** and **W3** preferably satisfy a relationship of $(W2 - W3) \leq 0.2 \times \lambda/NA$ as in Embodiment 1. Specifically, a difference between the line width **L5A** of the partial pattern **124A** and the line width **L5B** of the partial pattern **124B** is preferably not larger than $(0.2 \times \lambda/NA) \times M$. In this case, when the line widths of mask patterns are different between a densely arranged pattern region with a high close degree and a densely arranged pattern region with a low close degree although the widths of

desired patterns to be formed on a wafer are the same, and specifically, when the line width **L5A** of the partial pattern **124A** and the line width **L5B** of the partial pattern **124B** are different, the following architecture is preferably employed: A ratio **F5A/L5A** between the line width **L5A** of the mask pattern disposed in the densely arranged pattern region with a high close degree and the width **F5A** of the phase shifter provided in the vicinity of the center of this pattern (the phase shifter **102A**) is smaller than a ratio **F5B/L5B** between the line width **L5B** of the mask pattern disposed in the densely arranged pattern region with a low close degree and the width **F5B** of the phase shifter provided in the vicinity of the center of this pattern (the phase shifter **102B**).

Furthermore, this modification is described by exemplifying the case where the partial pattern **124A** included in the densely arranged patterns **152** with a high close degree and the partial pattern **124B** included in the densely arranged patterns **152** with a low close degree are both included in one continuous pattern, i.e., the pattern **124**. However, as far as the aforementioned relationships among the widths are satisfied, a pattern included in densely arranged patterns with a high close degree and a pattern included in densely arranged patterns with a low close degree may be different patterns disposed on one transparent substrate.

Moreover, the dimension **W0** is preferably not larger than 0.8 x λ/NA and more preferably not smaller than 0.3 x λ/NA and not larger than 0.6 x λ/NA also in this modification as in Embodiment 1.

In addition, the distance **S0** is preferably not larger than λ/NA also in this modification as in Embodiment 1.

When it is assumed that G2 > S0 and S0 > G1 in the architecture of this modification, the width of a phase shifter provided in densely arranged patterns arranged at a distance not smaller than the distance **S0** may be set to a value the same as that employed

in an isolated pattern, and therefore, the mask architecture may be set so that the value (F5B – F5A) can be in proportion to a value (S0 – G1).

Although this modification is described by exemplifying the case where the respective patterns are arranged at an equal distance in the densely arranged patterns, the architecture of this modification is applicable to densely arranged patterns composed of patterns arranged at irregular distances.

FIGS. **13A** through **13D** are diagrams for explaining a method for converting densely arranged patterns composed of patterns arranged at irregular distances into equivalent densely arranged patterns composed of patterns arranged at an equal distance.

First, in densely arranged patterns **161** of FIG. **13A**, distances from a target pattern **331** to different patterns **332** and **333** disposed to be close on both sides of the target pattern **331** are assumed to be distances **g1** and **g2**, respectively. In this case, when both the distances **g1** and **g2** are not larger than the distance **S0**, the densely arranged patterns **161** may be regarded as equivalent to densely arranged patterns **162** of FIG. **13B**. Specifically, in the densely arranged patterns **162**, distances from a target pattern **341** to different patterns **342** and **343** disposed to be close on both sides of the target pattern **341** are equal to be a distance **g0** = (g1 + g2)/2. The densely arranged patterns **161** and the densely arranged patterns **162** may be regarded as equivalent for the following reason: The mask architecture of this modification is devised in consideration of the diffraction, and the law of arithmetic mean works out in a physical phenomenon depending upon a pitch of cyclic arrangement. It is noted that the respective patterns **331** through **333** included in the densely arranged patterns **161** and the respective patterns **341** through **343** included in the densely arranged patterns **162** all have the mask enhancer structure in which a phase shifter **102** is provided at the center of a line-shaped shielding portion **101**.

In densely arranged patterns **163** of FIG. **13C**, distances from a target pattern **351**

to different patterns **352** and **353** disposed to be close on both sides of the target pattern **351** are assumed to be distances **g3** and **g4**, respectively. In this case, if g4 > S0 and S0 > g3, the densely arranged patterns **163** may be regarded as equivalent to densely arranged patterns **164** of FIG. **13D**. Specifically, in the densely arranged patterns **164**, distances from a target pattern **361** to different patterns **362** and **363** disposed to be close on both sides of the target pattern **361** are distances **g3** and **S0**, respectively. The densely arranged patterns **163** and the densely arranged patterns **164** may be regarded as equivalent for the following reason: In the case where a distance between patterns is larger than the distance **S0**, this case is optically equivalent to a case where a distance between patterns is the distance **S0**, and therefore, there is no need to directly consider a distance between patterns larger than the distance **S0** in the calculation performed for determining the width of a phase shifter. Furthermore, the densely arranged patterns **164** of FIG. **13D** may be converted into densely arranged patterns composed of patterns arranged at an equal distance (specifically, a distance of (g3 + S0)/2) in the same manner as in the conversion of the densely arranged patterns **161** of FIG. **13A** into the densely arranged patterns **162** of FIG. **13B**. It is noted that the respective patterns **351** through **353** included in the densely arranged patterns **163** and the respective patterns **361** through **363** included in the densely arranged patterns **164** all have the mask enhancer structure in which a phase shifter **102** is provided at the center of a line-shaped shielding portion **101**.

MODIFICATION 2 OF EMBODIMENT 1

A photomask according to Modification 2 of Embodiment 1 of the invention will now be described with reference to the accompanying drawings.

FIG. **14** is a plan view of the photomask of Modification 2 of Embodiment 1, and more specifically, a photomask provided with a mask pattern having the mask enhancer structure and included in densely arranged patterns. In FIG. **14**, a transparent substrate

100 is perspectively shown.

As shown in FIG. **14**, mask patterns (line patterns **131** through **135**) for forming desired line-shaped patterns on a wafer through exposure are drawn on the transparent substrate **100**. In this case, each of the line patterns **131** through **135** is basically made of a shielding portion **101**. Furthermore, a phase shifter **102** is provided at the center of a pattern region, having a line width not larger than a given dimension **W0**, of each of the line patterns **131** through **133**. Specifically, each of the line patterns **131** through **133** has the mask enhancer structure. For example, the pattern **131** is a pattern with a line width **L6** satisfying a relationship of $W2 \geq L6 > W3$ with respect to given dimensions **W2** and **W3** satisfying a relationship of $W0 \geq W2 > W3$, and the phase shifter **102** is provided at the center of the pattern **131**.

Also, as shown in FIG. **14**, the pattern **131** includes a partial pattern (mask enhancer close portion) **131A** close to different patterns **132** and **133** (having the mask enhancer structure) at a distance **G** ($S0 > G$) with a transparent portion sandwiched therebetween along a direction vertical to the line direction thereof. Furthermore, a phase shifter **102A** with a line width **F6A** is provided at the center of the partial pattern **131A**.

Furthermore, the pattern **124** includes a partial pattern (shielding pattern close portion) **131B** close to different patterns **134** and **135** (made of the shielding portion **101** alone) at the distance **G** ($S0 > G$) with the transparent portion sandwiched therebetween along the vertical direction. In other words, the pattern **131** including the partial patterns **131A** and **131B** is close to the different patterns **132** through **135** at an equal distance. Also, a phase shifter **102B** with a line width **F6B** is provided at the center of the partial pattern **131B**.

This modification is characterized by the architecture in which $F5B > F5A$. Specifically, the width of a phase shifter provided in a pattern included in densely arranged

patterns composed of patterns having the mask enhancer structure is smaller than the width of a phase shifter provided in a pattern included in densely arranged patterns composed of both a pattern having the mask enhancer structure and a simple shielding pattern.

In the above description, the respective line-shaped patterns are different patterns separated from one another. Also in this modification, however, in the case where a plurality of line-shaped rectangular regions belonging to a complicated polygonal pattern are regarded as a target, the aforementioned relationships may be satisfied in the respective line-shaped rectangular regions alone in the same manner as in Modification 1 of Embodiment 1. Also, the transparent portion between the line-shaped rectangular regions may be a transparent portion surrounded with the shielding portion **101** such as the transparent portion disposed within the frame-like pattern **113** shown in FIG. **2**.

According to this modification, the width of a phase shifter provided in a pattern having the mask enhancer structure (the pattern **131**) is smaller in the case where another close pattern has the mask enhancer structure than in the case where another close pattern is made of a shielding portion. In other words, as the shielding property of another pattern is higher, the width of a phase shifter provided in the pattern **131** is smaller. Therefore, in accordance with the degree at which light (in an identical phase with respect to the transparent portion) rounding to the back side of the pattern **131** through the transparent portion disposed around the pattern **131** is reduced owing to another pattern, light (in an opposite phase with respect to the transparent portion) passing through the inside of the pattern **131** (the phase shifter **102**) can be reduced. Accordingly, the shielding property of the pattern **131** can be sufficiently improved, and hence, an exposure margin is increased and contrast in a light intensity distribution formed in the exposure is improved. In other words, also in a photomask including not only isolated patterns but also complicated patterns close to one another, the effect to increase the process margin can

be sufficiently attained by employing the mask enhancer structure. Also, since the width of the phase shifter included in the mask enhancer structure can be optimized in accordance with the shielding property of another adjacent pattern, a photomask capable of fine pattern formation with random pattern layout can be realized.

Furthermore, according to this modification, with respect to a pattern having the mask enhancer structure and included in densely arranged patterns compose of a plurality of patterns arranged at arbitrary distances, a photomask capable of maximizing an exposure margin can be realized. Accordingly, good pattern formation characteristics attained by the mask enhancer structure of a fine mask pattern can be exhibited even when respective mask patterns are in an arbitrary close relationship, and hence, a photomask capable of fine pattern formation can be realized.

Although the mask enhancer structure is described to be composed of a shielding portion and a phase shifter in this modification, the shielding portion may be replaced with a semi-shielding portion.

Moreover, in this modification, both of the partial pattern **131A** and the partial pattern **131B** included in the pattern **131** have the line width **L6**. However, the line widths of the partial patterns **131A** and **131B** may be different as far as they are larger than the dimension **W3** and not larger than the dimension **W2**. Specifically, assuming that the partial pattern **131A** has a line width **L6A** and the partial pattern **131B** has a line width **L6B**, there may be a relationship of $L6A \neq L6B$ as far as $W2 \geq L6A > W3$ and $W2 \geq L6B > W3$. Also, the given dimensions **W2** and **W3** preferably satisfy a relationship of $(W2 - W3) \leq 0.2 \times \lambda/NA$ as in Embodiment 1. Specifically, a difference between the line width **L6A** of the partial pattern **131A** and the line width **L6B** of the partial pattern **131B** is preferably not larger than $(0.2 \times \lambda/NA) \times M$. In this case, when the line width **L6A** of the partial pattern **131A** (the mask enhancer close pattern) is different from the line width **L6B**

of the partial pattern **131B** (the shielding portion close pattern) although the widths of desired patterns to be formed on a wafer are the same, the following architecture is preferably employed: A ratio **F6A/L6A** between the line width **L6A** of the partial pattern **131A** corresponding to the mask enhancer close portion and the width **F6A** of the phase shifter provided in the vicinity of the center of this pattern (the phase shifter **102A**) is smaller than a ratio **F6B/L6B** between the line width **L6B** of the partial pattern **131B** corresponding to the shielding pattern close portion and the width **F6B** of the phase shifter provided in the vicinity of the center of this pattern (the phase shifter **102B**).

Furthermore, this modification is described by exemplifying the case where the partial pattern **131A** corresponding to the mask enhancer close portion and the partial pattern **131B** corresponding to the shielding pattern close portion are both included in one continuous pattern, i.e., the pattern **131**. However, as far as the aforementioned relationships among the widths are satisfied, a pattern corresponding to a mask enhancer close portion and a pattern corresponding to a shielding pattern close portion may be different patterns disposed on one transparent substrate.

Moreover, the dimension **W0** is preferably not larger than 0.8 x λ/NA and more preferably not smaller than 0.3 x λ/NA and not larger than 0.6 x λ/NA also in this modification as in Embodiment 1. The distance **S0** is preferably not larger than λ/NA as in Embodiment 1.

In addition, the distance **S0** is preferably not larger than λ/NA also in this modification as in Embodiment 1.

EMBODIMENT 2

A pattern formation method according to Embodiment 2 of the invention, and more specifically, a pattern formation method using the photomask of Embodiment 1 (hereinafter referred to as the photomask of the invention) will now be described with

reference to the accompanying drawings.

FIGS. **15A** through **15D** are cross-sectional views for showing procedures in the pattern formation method of Embodiment 2.

First, as shown in FIG. **15A**, a target film **501** of, for example, a metal film or an insulating film is formed on a substrate **500**, and thereafter, a positive resist film **502** is formed on the target film **501** as shown in FIG. **15B**.

Next, as shown in FIG. **15C**, the photomask of this invention such as the photomask of Embodiment 1 shown in FIG. **3B** is irradiated with exposing light **503**, so as to expose the resist film **502** to transmitted light **504** having passed through the photomask.

It is noted that line-shaped mask patterns to be transferred through the exposure are provided on a transparent substrate **100** of the photomask used in the procedure of FIG. **15C**. The mask patterns are made of a shielding portion **101** alone or a combination of the shielding portion **101** and a phase shifter **102**. Furthermore, the phase shifter **102** is formed so as to be surrounded with the shielding portion **101**. In other words, the mask pattern has the mask enhancer structure composed of the shielding portion **101** and the phase shifter **102**. Also, the phase shifter **102** is formed by, for example, trenching the transparent substrate **100**.

Furthermore, in the exposure procedure shown in FIG. **15C**, the resist film **502** is subjected to the exposure by using, for example, an oblique incident exposure light source. In this case, as shown in FIG. **15C**, merely a latent image portion **502a** of the resist film **502** corresponding to a region excluding the mask patterns is irradiated at exposure energy sufficiently high for allowing the resist to dissolve in development.

Next, the resist film **502** is developed so as to remove the latent image portion **502a**, thereby forming resist patterns **505** corresponding to the mask patterns as shown in FIG. **15D**.

Since the photomask of this invention (specifically, the photomask of Embodiment 1) is used in the pattern formation method of Embodiment 2, the same effects as those attained in Embodiment 1 can be attained. Also, when the substrate (the wafer) on which the resist is applied is subjected to the oblique incident exposure through the photomask of this invention, the portion of the resist corresponding to the region excluding the mask enhancer is irradiated at the exposure energy sufficiently high for allowing the resist to dissolve in the development because the mask enhancer including the phase shifter (an opening) **102** has a very high shielding property. Furthermore, contrast of a shielded image formed by the mask enhancer is very high and the shielded image has a good defocus characteristic, and therefore, fine pattern formation with a high DOF can be realized.

Although the photomask having the mask enhancer structure composed of the shielding portion **101** and the phase shifter **102** is used in Embodiment 2, a photomask having the mask enhancer structure composed of a semi-shielding portion and a phase shifter may be used instead.

Furthermore, although the positive resist process is employed in Embodiment 2, the same effects can be attained by employing negative resist process.

Also, in Embodiment 2, the oblique incident illumination (oblique incident exposure) is preferably employed in the procedure for irradiating with the exposing light shown in FIG. **15C**. Thus, the contrast between portions respectively corresponding to the mask pattern and the transparent portion is improved in a light intensity distribution of the light passing through the photomask of this invention. Furthermore, the focus characteristic of the light intensity distribution is also improved. Accordingly, the exposure margin and the focus margin are improved in the pattern formation. In other words, fine pattern formation with good defocus characteristics can be realized.

Moreover, even in the case where patterns having the mask enhancer structure are close to each other on the photomask, the contrast of the respective patterns is largely improved in the exposure.

Herein, a light source for the oblique incident exposure means a light source as shown in any of FIGS. **16B** through **16D** obtained by removing a vertical incident component (a component of the exposing light vertically entering the photomask from the light source) from a general exposure light source of FIG. **16A**. Typical examples of the light source for the oblique incident exposure are an annular exposure light source of FIG. **16B** and a quadrupole exposure light source of FIG. **16C**. Although slightly depending upon a target pattern, the quadrupole exposure light source is generally more effectively used than the annular exposure light source for improving the contrast and increasing the DOF. However, the quadrupole exposure has a side effect to, for example, distort a pattern shape against a mask shape, and hence in such a case, an annular/quadrupole exposure light source of FIG. **16D** is preferably used. As a characteristic of this annular/quadrupole exposure light source, assuming the XY coordinate system with the center of the light source (the center of a general exposure light source) corresponding to the origin, the annular/quadrupole exposure light source has a characteristic of the quadrupole exposure light source since portions at the center and on the X and Y axes of the light source are removed, and has a characteristic of the annular exposure light source since the outline of the light source is in a circular shape.

EMBODIMENT 3

A mask data generation method according to Embodiment 3 of the invention, and more specifically, a mask data generation method for the photomask of Embodiment 1 (hereinafter referred to as the photomask of this invention) will now be described with reference to the accompanying drawings. It is noted in this embodiment that the

functions, the characteristics and the like of respective elements of the photomask are the same as those of the corresponding elements of the aforementioned photomask of this invention unless otherwise mentioned.

Before describing specific process contents, significant points of the mask data generation method for the photomask of this invention will be described. In the case where pattern formation is carried out by using a mask pattern having the mask enhancer structure, the width of a phase shifter and the width of a shielding portion or a semi-shielding portion surrounding the phase shifter in the mask enhancer structure affect even in forming one isolated pattern. Therefore, it is necessary to determine a plurality of element values such as the width of the phase shifter and the width of the shielding portion or the semi-shielding portion for attaining a desired value as a dimension of a pattern to be formed, namely, a CD (critical dimension). Furthermore, in many cases, there are not only one but a plurality of combinations of the element values for realizing the desired CD. Accordingly, in this embodiment, elements significant for maximizing a margin in the pattern formation are priorly determined, and thereafter, the pattern dimension is adjusted by using elements less affecting the margin in the pattern formation.

Specifically, it is preferred that the layout position and the width of the phase shifter are first determined as elements largely affecting the margin in the pattern formation, and thereafter, the width of the shielding portion or the semi-shielding portion surrounding the phase shifter, namely, the width of a region sandwiched between the phase shifter and a transparent portion, is adjusted so as to generate mask data for realizing a desired CD. Through such mask data generation, while attaining highly precise pattern dimension control, mask data for realizing a photomask for attaining a large margin in the pattern formation can be generated. Now, the specific process contents will be described.

FIG. **17** is a flowchart of the mask data generation method of Embodiment 3, and

more specifically, a method for generating LSI mask patterns corresponding to shielding patterns on a mask on the basis of fine desired patterns. Also, FIGS. **18A** through **18F** are diagrams of examples of specific mask patterns generated in the respective procedures in the mask data generation method of Embodiment 3.

FIG. **18A** shows desired patterns to be formed by using mask patterns. In other words, patterns **600** of FIG. **18A** are patterns corresponding to regions where a resist is not to be exposed in the exposure using the photomask of the invention (desired unexposed regions). In the description of the pattern formation in this embodiment, the positive resist process is premised to employ unless otherwise mentioned. Specifically, the description is given on the assumption that an exposed portion of a resist is removed through development so as to allow an unexposed portion of the resist to remain as a resist pattern. Accordingly, in the case where the negative resist process is employed, mask data can be generated basically in the same manner as in this embodiment by regarding that an exposed portion of a resist remains as a resist pattern with an unexposed portion of the resist removed.

First, in step S1, the desired patterns **600** of FIG. **18A** are input to a computer used for the mask data generation.

Next, in step S2, the desired patterns of FIG. **18A** are resized to be enlarged or reduced depending upon whether over-exposure or under-exposure is performed in the exposure of the created photomask. Alternatively, the patterns may be resized for intentionally adjusting dimensions at the stage of lithography in consideration of dimensional change occurring in various processes performed after the pattern formation such as dry etching and CMP. FIG. **18B** shows patterns (shielding patterns) **601** resulting from the resizing.

Then, in step S3, a phase shift pattern **602** is generated at the center of a region,

having a dimension (a width) not larger than a given value, of each pattern **601** as shown in FIG. **18C**. Specifically, the shape (the layout position, the width and the like, which also applies the following description) of a phase shifter included in the mask enhancer structure is determined. At this point, the phase shift pattern **602** is completely contained within the pattern **601**, namely, within the shielding pattern. In this embodiment, it is assumed that each pattern **601** is composed of a plurality of independent line-shaped patterns and that the width of the pattern **601** means a line width thereof (which also applies to the width of the phase shift pattern **602**). A line-shaped pattern herein means not only a pattern having a line-shaped outline but also a rectangular region included in an arbitrary pattern and having a length not smaller than twice of the wavelength of exposing light. Also, a distance between patterns means not only a distance between patterns separated from each other but the width of a transparent portion sandwiched between line-shaped rectangular regions in a pattern such as the frame-like pattern **113** shown in FIG. **2** (a frame-shaped pattern) is also defined as a distance between patterns.

The width of the phase shift pattern **602** can be set, for example, as follows: At least one given dimension **W0** is determined, and a phase shift pattern **602** with a width of a given dimension **F0** (W0 > F0) is disposed in a region, having a width not larger than the dimension **W0**, of the pattern **602**. Also, preferably at least two given dimensions **W0** and **W1** (W0 > W1) are determined, and a phase shift pattern **602** with a width of the given dimension **F0** is disposed in a region, having a width larger than the dimension **W1** and not larger than the dimension **W0**, of the pattern **601** and a phase shift pattern **602** with a width of a given dimension **F1** (F1 > F0) is disposed in a region, having a width not larger than the dimension **W1**, of the pattern **601**. Furthermore, in consideration of the principle of the mask enhancer, it goes without saying that a method in which three or more given dimensions (**W0**, **W1**, **W2**, ... etc.: W0 > W1 > W2 ... etc.) are determined and a phase

shift pattern with a larger width is provided in a region, having a width not larger than the dimension **W0**, of the pattern **601** as the width of the region is smaller (in other words, a thinner phase shift pattern is provided as the width of a mask pattern is larger) is preferred.

Next, in step S4, the width of each phase shift pattern **602** is adjusted in accordance with the close relationship between the line-shaped patterns included in the patterns **601** as shown in FIG. **18D**. Specifically, the width of the phase shift pattern **602** provided in one line-shaped pattern is adjusted on the basis of a distance from this line-shaped pattern to a different line-shaped pattern close to it with a transparent portion (a region where no pattern **601** is present in this embodiment) sandwiched therebetween. In FIG. **18D**, a phase shift pattern **603** is a phase shift pattern having been adjusted in the dimension.

The specific method for adjusting the width of the phase shift pattern is as follows: At least one given distance **S0** is determined, and when the line-shaped pattern including the phase shift pattern to be adjusted (a target pattern) is not close to a different line-shaped pattern (a different pattern) at a distance not larger than the distance **S0**, the width of the phase shift pattern is set to **F0A**, and when the target pattern is close to a different pattern at a distance not larger than the distance **S0**, the width of the phase shift pattern is set to **F0B** (F0A > F0B). Also, preferably at least two given distances **S0** and **S1** (S0 > S1) are determined, and when the target pattern is not close to a different pattern at a distance not larger than the distance **S0**, the width of the phase shift pattern is set to **F0A**, when the target pattern is close to a different pattern at a distance larger than the distance **S1** and not larger than the distance **S0**, the width of the phase shift pattern is set to **F0B**, and when the target pattern is close to a different pattern at a distance not larger than the distance **S1**, the width of the phase shift pattern is set to **F0C** (F0B > F0C). Furthermore, as described in Embodiment 1, it goes without saying that a method in which

three or more given distances (**S0, S1, S2,** ... etc.: S0 > S1 > S2 ... etc.) are determined and the width of a phase shift pattern is set to be smaller as the distance between the target pattern and a different pattern is smaller is preferred.

Furthermore, in addition to the aforementioned adjustment of the width of the phase shift pattern, the width of the phase shift pattern is preferably adjusted as follows in accordance with whether a different pattern close to the target pattern is a simple shielding pattern or a pattern having the mask enhancer structure including a phase shift pattern: Whether or not a phase shift pattern is also disposed in a different pattern close to the target pattern in which the phase shift pattern is disposed can be determined depending upon the width of the different pattern. Accordingly, in the case where a different close pattern has a width larger than the given dimension **W0** (namely, in the case where a phase shift pattern is not disposed in the different pattern), the width of the phase shift pattern disposed in the target pattern is set to **F0B**, and in the case where the different close pattern has a width not larger than the given dimension **W0** (namely, in the case where a phase shift pattern is disposed in the different pattern), the width of the phase shift pattern disposed in the target pattern is set to **F0M** (F0B > F0M).

Moreover, in the case where there are different close patterns on respective sides of the target pattern, the width of the phase shift pattern is preferably adjusted as follows: Distances **S1** and **S2** from the respective different patterns close on the sides of the target pattern to the target pattern are obtained, and the width of the phase shift pattern is set to be smaller when a value **(S1 + S2)/2** is not larger than a given value than when the value **(S1 + S2)/2** is larger than the given value. Alternatively, in consideration that distances to the different patterns disposed on the side of the target pattern are preferably averaged in evaluation of the distances between the target pattern and the different patterns in the adjustment of the width of the phase shift pattern, the following adjustment may be

employed in stead of the aforementioned adjustment: In the case where a distance to, for example, a different pattern disposed on the left hand side of the target pattern is a distance **S1** and a distance to a different pattern disposed on the right hand side of the target pattern is a distance **S2**, the width of the phase shift pattern provided in the target pattern is assumed to be **F**. Also, in the case where distances to the different patterns disposed on the respective sides of the target pattern are both a distance **S1**, the width of the phase shift pattern provided in the target pattern is assumed to be **F1**, and in the case where distances to the different patterns disposed on the respective sides of the target pattern are both a distance **S2**, the width of the phase shift pattern provided in the target pattern is assumed to be **F2**. On these assumption, the width of the phase shift pattern is preferably adjusted so that $F = (F1 + F2)/2$. Furthermore, in the aforementioned averaging, when the distance **S1** or **S2** is not smaller than the given distance **S0**, the distances are preferably averaged by regarding the distance **S1** or **S2** as the distance **S0**.

Through the aforementioned processes in steps S3 and S4, the layout position and the width of a phase shifter largely affecting the margin in the pattern formation can be optimally determined.

Next, in step S5, on the basis of the shape of the phase shift pattern **603** determined up to step S4, a shielding pattern **604** corresponding a portion of the pattern (the shielding pattern) **601** excluding the phase shift pattern **603** is defined as shown in FIG. **18E**. Subsequently, preparations are made for a process to adjust the dimension of the mask pattern so as to form a pattern with a desired dimension correspondingly to the mask pattern through the exposure by using the photomask fabricated by the mask data generation method of this embodiment (the photomask of this invention). Specifically, preparations are made for processing generally designated as OPC (optical proximity correction). In this embodiment, the boundary between a shielding portion and a

transparent portion alone is moved in adjusting the dimension of the mask pattern on the basis of a predicted dimension obtained in the pattern formation (the dimension of a resist pattern), namely, a predicted CD. Therefore, in step S5, an edge corresponding to the boundary of the shielding pattern **604** with the transparent portion is set as a CD adjustment edge **605**. Thus, the CD can be adjusted in accordance with the width of the shielding pattern **604** sandwiched between the phase shift pattern **603** and the transparent portion in the pattern region where the phase shift pattern **603** is disposed. Accordingly, without deforming the phase shift pattern **603** whose width has been adjusted in accordance with the close relationship between patterns, a mask pattern for realizing the desired CD can be generated. It goes without saying that the shielding pattern **604** may be replaced with a semi-shielding pattern.

Next, in step S6, the transmittance of the phase shift pattern **603** disposed in the mask pattern, namely, the transmittance of the phase shifter, is set.

Then, in steps S7, S8 and S9, the OPC processing (such as model base OPC processing) is carried out. Specifically, in step S7, a dimension of a resist pattern formed in the exposure by using the pattern including the shielding pattern **604** and the phase shift pattern **603** is predicted through simulation performed in consideration of the optical principle and a resist development characteristic. At this point, not only the lithography but also other processes related to the pattern formation such as dry etching may be taken into consideration in the simulation. Subsequently, in step S8, it is determined whether or not the predicted dimension of the resist pattern accords with a desired dimension. When the predicted dimension does not accord with the desired dimension, the CD adjustment edge **605** is moved in step S9 on the basis of a difference between the predicted dimension of the resist pattern and the desired dimension, so as to deform the shielding pattern **604**, namely, the mask pattern.

Since the phase shift pattern is previously generated in this embodiment, if the width of the phase shift pattern is inappropriately set in steps S3 and S4, the desired CD cannot be obtained in steps S7 through S9. In such a case, the inappropriate width of the phase shift pattern may be corrected. It is noted that an inappropriate phase shifter is a phase shifter that makes a predicted CD larger than a desired CD even when the width of a shielding portion surrounding the phase shifter is 0. Therefore, when the inappropriate phase shifter has been generated, a desired CD cannot be obtained unless the width of the phase shifter is reduced. Accordingly, the line width of the phase shift pattern generated in steps S3 and S4 is preferably set so that a predicted CD cannot exceed a desired CD even when there is no shielding portion around the phase shift pattern. When such a phase shift pattern is generated, there is no need to correct the phase shift pattern in carrying out the processes of steps S7 through S9. At this point, the maximum width of a phase shifter that does not make a predicted CD exceed a desired CD when the mask pattern is composed of the phase shifter alone is designated as a maximum phase shifter width against a CD value. Specifically, the width of the phase shift pattern generated in steps S3 and S4 is preferably set not to exceed the maximum phase shifter width against the CD value. It is noted that the maximum phase shifter width against the CD value can be easily obtained through simulation or the like after determining the transmittance of the phase shifter and exposing conditions.

As described so far, as a characteristic of this embodiment, a mask pattern capable of forming a resist pattern with a desired dimension is realized by changing merely the CD adjustment edge **605** set in step S5 in the phase shift pattern **603** determined up to step S4. In other words, when the processes of steps S7 through S9 are repeated until the predicted dimension of the resist pattern accords with the desired dimension, a mask pattern capable of forming a resist pattern with a desired dimension is ultimately output in step S10. FIG.

18F shows an example of the mask pattern output in step S10. As shown in FIG. **18F**, a shielding portion **101** made of a Cr film or the like is formed in a region corresponding to the shielding pattern **604** on a transparent substrate **100**. Also, a phase shifter **102** formed by, for example, trenching the transparent substrate **100** is formed in a region corresponding to the phase shift pattern **603** on the transparent substrate **100**.

In FIG. **18F**, an end portion **610** of the line-shaped pattern having the mask enhancer structure composed of the shielding portion **101** and the phase shifter **102** is in a hammer-like shape with a large width, which shape is employed for preventing the resist pattern corresponding to the line end portion **610** from receding. Also, in such a line end portion in a hammer-like shape, even when its line width exceeds the given value, a phase shifter for improving the shielding property may be disposed at its center. This is for the following reason: In a general line pattern, light rounds along two directions (in directions vertical to the line direction) through transparent portions disposed on respective sides, but in a line end portion, light rounds along not only the two directions but also through a transparent portion disposed on an end side of the line, namely, along three directions. Therefore, a phase shifter can be disposed even when it has a width exceeding the given dimension.

As described above, according to Embodiment 3, in order to realize a mask good at significant pattern formation characteristics such as contrast, the width and the layout position of a phase shift pattern, that is, significant parameters, are first determined. Thereafter, merely the outermost edge of the pattern **601** set as the CD adjustment edge **605** is moved for the pattern dimension control. Therefore, a mask pattern capable of forming a desired fine pattern without changing the width and the like of the phase shift pattern once determined, namely, while retaining conditions for exhibiting the good pattern formation characteristics, can be realized. In other words, a mask pattern capable of

forming a desired fine pattern and having the good pattern formation characteristics can be realized.

Furthermore, according to Embodiment 3, the width of the phase shifter of the mask enhancer structure is adjusted on the basis of a distance from a different close pattern to the pattern having the mask enhancer structure (the target pattern). Specifically, the width of the phase shifter is reduced as the distance from the different pattern is smaller. Therefore, in accordance with the degree at which light (in an identical phase with respect to a transparent portion) rounding to the back side of the target pattern through the transparent portion disposed around the target pattern is reduced owing to the presence of the different pattern, light (in an opposite phase with respect to the transparent portion) passing through the inside of the target pattern (the phase shifter) can be reduced. Accordingly, the shielding property of the target pattern can be sufficiently improved, so that the exposure margin can be increased and the contrast in a light intensity distribution formed in the exposure can be improved. Specifically, in a photomask including not only an isolated pattern but also complicated patterns close to one another, the good pattern formation characteristics can be realized. Also, since the width of the phase shifter of the mask enhancer structure can be optimized in accordance with the close relationship between patterns, a photomask capable of fine pattern formation with random pattern layout can be realized.

Although the mask pattern having the mask enhancer structure using a shielding portion is described in Embodiment 3, this embodiment may be applied to a mask pattern having the mask enhancer structure using a semi-shielding portion instead. Specifically, portions described as the shielding portion of the mask enhancer structure in this embodiment may be all replaced with semi-shielding portions.

Moreover, in each of Embodiments 1 through 3, the description is given with

respect to a transmission photomask, which does not limit the invention. The present invention is applicable to a reflection mask by replacing all the transmission phenomenon of exposing light with the reflection phenomenon by, for example, replacing the transmittance with reflectance.

Industrial Applicability

As described so far, the present invention relates to a photomask, a pattern formation method and a mask data generation method using the photomask, and is useful particularly for, for example, application to fine pattern formation employed in fabrication of a semiconductor integrated circuit device or the like.